Spatial and Temporal Variation in Economically Optimum Nitrogen Rate for Corn

M. Mamo,* G. L. Malzer, D. J. Mulla, D. R. Huggins, and J. Strock

ABSTRACT

The economically optimum N rate (EONR) required for corn (*Zea mays* L.) may vary spatially due to variation in soil characteristics and temporally due to the interactions of environmental factors. The objectives of this research were to quantify the impact of field variability on the yield response of corn to N fertilization and to evaluate the temporal stability of these response functions. A production field near Revere, MN, was cropped with corn in 1995, 1997, and 1999 in rotation with soybean [*Glycine max* (L.) Merr.]. Four replications of seven treatments were established in a split-plot arrangement of a randomized complete block design. Main plots consisted of three N rates (0, 67, 134, and 202 kg ha^{-1}) while the split plots were two rates (0 and 0.56 kg ha^{-1}) of nitrapyrin [2-chloro-6 (trichloromethyl)-pyridine]. Each replication was divided into subblocks to estimate spatial patterns in yield N response and EONR. Spatial analysis indicated that only half of the field responded to N. Uniform application recommendation of 145 kg N ha^{-1} for the whole field overfertilized these areas while other areas were underfertilized. Variable-rate N applications according to the EONR would have resulted in 69 and 75 kg ha^{-1} less N being applied than the uniform N rate in 1997 and 1999, respectively. Potential economic benefits were \$8 and \$23 ha^{-1} higher than the uniform N rate in 1997 and 1999, respectively. Approximately 60% of the field responded in a similar manner in both 1997 and 1999, suggesting that temporal variations must also be considered with site-specific N management.

Nitrogen fertilizer needs of corn may vary both between fields (Bundy and Andraski, 1995; Schmitt and Randall, 1994) and within fields (Blackmer and White, 1998; Malzer et al., 1996). When uniform application rates of N are made across a field with variable soil and plant N relations, the results will be overfertilization in some areas and underfertilization in others (Fiez et al., 1995; Pan et al., 1997). Overapplication of N increases the probability of NO_3–N leaching below the root zone (Meisinger and Randall, 1991) while underfertilization limits yields (Pan et al., 1997) and may restrict economic returns (Scharf and Lory, 2000).

Differential responses to fertilizer N both between and within fields are due to both spatial and temporal variations in crop demand (Fiez et al., 1995) and soil N supply and losses (Hergert et al., 1995). Spatial soil variability may influence yield potential, N requirements, mineralization of organic N, and available soil N (Fiez et al., 1994) while temporal variability may influence the expression of spatial variability (Eghball and Varvel, 1997). Because N losses from soils via leaching and denitrification may be both spatially and temporally affected, it would suggest that the benefits associated with a nitrification inhibitor may also be spatially and temporally influenced.

The potential economic and environmental benefits associated with site-specific N rate management will depend on the ability to predict and/or define the magnitude of these dynamic soil and crop process. Therefore, the objectives of this research were to quantify the impact of field variability on the yield response of corn to N fertilization (EONR and profitability) for a location in southwest Minnesota and to evaluate the temporal stability of these response functions across separate growing seasons.

MATERIALS AND METHODS

Site and Experimental Design

An experiment was established on a production field near Revere, MN (44°14′ N, 95°21′ W), beginning in 1994. The soils at the site belong to the Canisteo-Ves association and are nearly level to gently sloping. The three major soils present at the site are the Ves loam (fine-loamy, mixed, mesic Udic Haplustolls) with 27 g kg^{-1} organic matter (OM), the Webster clay loam (fine-loamy, mixed, mesic Typic Haplaquolls) with 40 g kg^{-1} OM, and the Normania loam (fine-loamy, mixed, mesic Aquic Haplustolls) with 33 g kg^{-1} OM. Normal annual precipitation is about 635 mm and is adequate for soybean, corn, and small grains because 80% of annual rainfall occurs during the growing season from April to September. Growing season monthly precipitation and temperature at the experimental site for 1995, 1997, and 1999 are presented in Fig. 1. The crop sequence was corn–soybean alternating each year.

Four replications of seven treatments were established in a split-plot arrangement of a randomized complete block design. Main-plot treatments consisted of four N rates (0, 67, 134, and 202 kg ha^{-1}) while the split plots were two rates (0 and 0.56 kg ha^{-1}) of nitrapyrin applied with each N rate. Each replication was further divided into 15 subblocks in space that was 15 m long and 42.7 m wide (Fig. 2) to facilitate spatial interpretation of yield response to applied N. In 1995, only three N rates (0, 67, and 134 kg N ha^{-1}) were used. All treatments were applied in strips 225 m long and 6.1 m wide in the fall before the corn year; however, in 1995, two rates (67 and 134 kg N ha^{-1}) were also applied in the spring. Each strip consisted of eight corn rows planted at 0.76-m spacing. The treatments remained in the same strips all three years, and N carryover effect was assumed to be negligible because soybean was cropped in alternate years with corn. Anhydrous ammonia was used as the N source and applied with a radar-controlled variable-rate applicator to compensate for variations in speed and to ensure a constant rate of N within each strip. In 1997 and 1999, preplant [Double Play—670 g L^{-1} EPTC (*S*-ethyl dipropylthiocarbamate) plus 170 g L^{-1} acetochlor (2-chloro-*N*-ethoxymethyl-6′-ethylacet-*o*-toluidide)] and postemergence {Pursuit—240 g L^{-1} imazethapyr [(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridine-

M. Mamo, Dep. of Agron. and Hortic., Univ. of Nebraska, Lincoln, NE 68583-0915; G.L. Malzer, D.J. Mulla, and J. Strock, Dep. of Soil, Water, and Climate, Univ. of Minnesota, 1991 Upper Buford Circle, St. Paul, MN 55108; and D.R. Huggins, USDA-ARS, Washington State Univ., Pullman, WA 22222. Contrib. from the Dep. of Soil, Water, and Climate, Univ. of Minnesota, and the Minnesota Agric. Exp. Stn. Received 4 June 2002. *Corresponding author (mmamo3@unl.edu).

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Abbreviations: EONR, economically optimum nitrogen rate; OM, organic matter; YEONR, yield at economically optimum nitrogen rate.

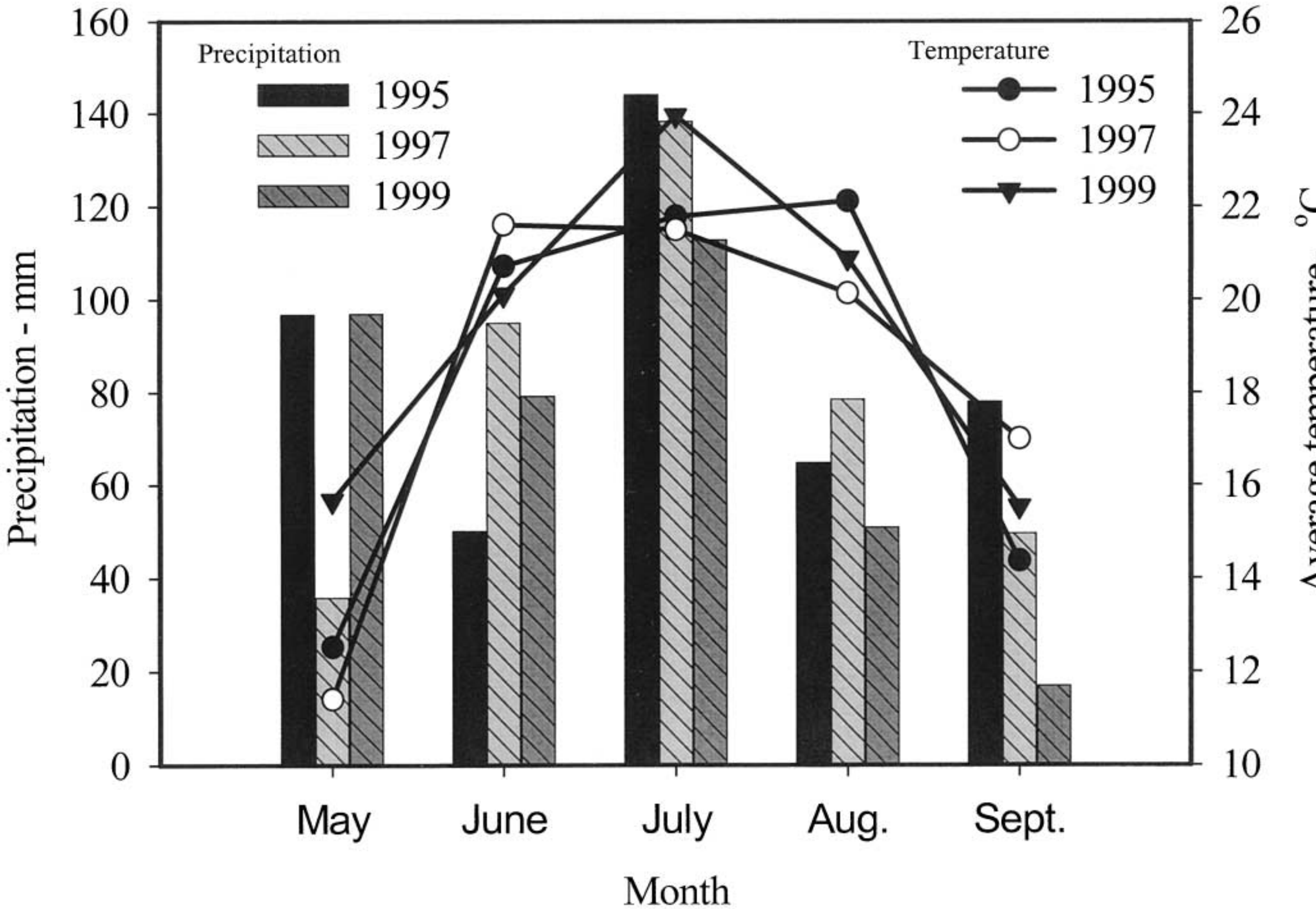

Fig. 1. Monthly precipitation and temperature at the experimental site during the 1995, 1997, and 1999 growing seasons. Bars and lines represent precipitation and temperature, respectively.

carboxylic acid]} herbicides were applied at 5.8 and 0.22 L ha^{-1}, respectively. In 1995, 2.6 L ha^{-1} Extrazine {cyanazine [2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-YL]amino]-2-methyl-propanenitrile] + atrazine (6-chloro-N^2-ethyl-N^4-isopropyl-1,3,5-triazine-2,4-diamine)} and 1.2 L ha^{-1} Banvil [480 g L^{-1} dicamba (3,6-dichloro-2-methoxybenzoic acid)] postemergence herbicides were applied. Complete details of the cultural practices of the field are listed in Table 1.

Crop Harvest

Grain yield was determined in 15-m segments through each treatment. Grain yield was measured from the two center rows of a strip in a subblock-by-subblock fashion using a Model 8 Massey Ferguson plot combine (AGCO Corp., Duluth, GA) equipped with a ground distance monitor and a computerized HarvestMaster weigh cell (HarvestMaster, Logan, UT). Every 15 m, the combine was stopped and the harvested grain weighed. Grain subsamples were collected from each harvest segment and dried at 60°C in a forced-air oven for 1 wk, and grain yield was adjusted to 15.5% moisture.

Statistical Analysis

Yield response functions were analyzed by using a mixed model of SAS (Littell et al., 1999; SAS Inst., 1996). Spatial analysis using nearest-neighbor analysis (Bhatti et al., 1991) was used to evaluate treatment effects on yield. Incorporation of spatial correlation in the statistical analysis reduces experimental error, which in turn will improve the probability and confidence of measuring treatment differences (Bhatti et al., 1991). For lack of a better term, the word residual denotes the difference between a yield value and its nearest two neighbors. In this experiment, the residual of a treatment in a subblock was calculated as the difference between its value and the average value of its two nearest subblocks having the same treatment (i.e., in the same north–south strip). The north and south neighbors were used because they were the two most adjacent subblocks having the same treatment (Fig. 2). The nearest-neighbor analysis used the residuals as a covariate in the analysis of covariance (Littell et al., 1999). An F statistic with $P \leq 0.100$ value was used to determine differences among treatments. A t test

Table 1. Cultural practices at experimental site in corn years.

Year	Tillage	Planting date	Hybrid	Planting rate	Starter fertilizer†
				seeds ha^{-1}	kg ha^{-1}
1995	Field cultivation	6 May 1995	‘Pioneer 3751’	71 630	70 (7–23–5)
1997	Chisel plow	25 Apr. 1997	‘4640 Ciba BT’	74 100	80 (7–34–0)
1999	Chisel plow	29 Apr. 1999	‘Novartis 4640 BT’	74 100	80 (10–34–0)

† Starter fertilizer applied as N–P_2O_5–K_2O.

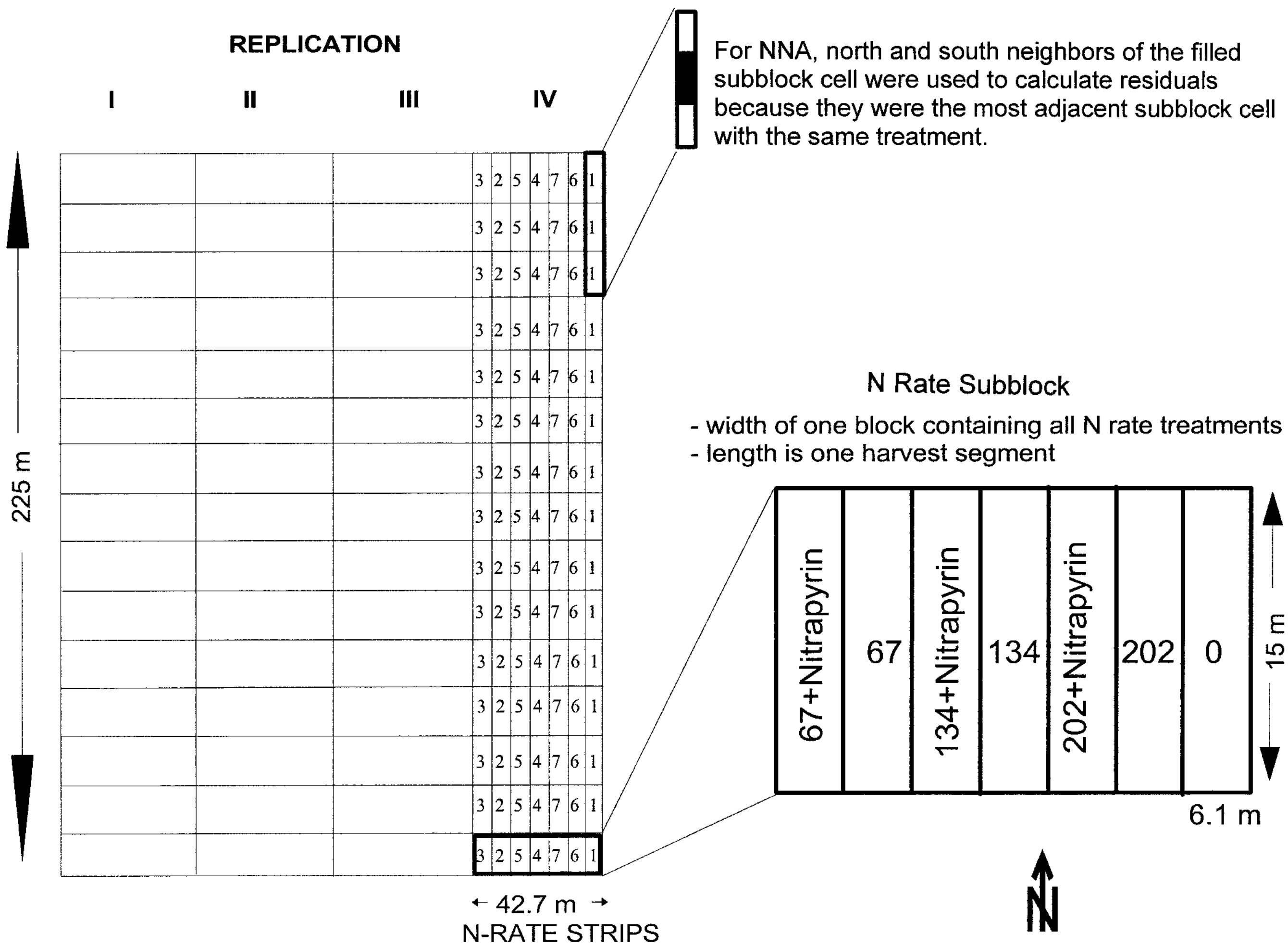

Fig. 2. Diagram of experimental design. NNA, nearest-neighbor analysis.

least square means (LSMEANS) statistic with $P \leq 0.100$ was used for differences between two treatments.

Yield Response-Curve Models

The yield response to treatments (N rate and N rate plus nitrapyrin) for each subblock was analyzed using an unfixed model where the yields of subblocks were best fit according to the significance of function parameters (i.e., coefficients of yield functions). Three models were used: no response, simple linear, and quadratic. The response curves were generated using the backward stepwise regression analysis of SAS (SAS Inst., 1996) to generate yield function equations based on the significance of coefficients. The significance of response-curve parameters was determined at a 10% probability level ($P = 0.100$). The N response functions for each subblock were determined for the 1997 and 1999 yield data. In 1995, only three N treatments were applied in the fall; therefore, the determination of EONR was viewed as marginal for the limited data set. Although yield response functions could have been improved by having more N rate treatments than were used in 1997 and 1999, the increased area needed to accommodate additional N treatments would have added more soil spatial variability into the subblocks, decreasing the precision of the response functions.

Economically Optimum Nitrogen Rate and Yield at Economically Optimum Nitrogen Rate

The EONR was calculated for N rate and N rate plus nitrapyrin treatments. The yield response to N and N plus nitrapyrin was calculated for each of the 60 subblocks (15 subblocks per replication). If the yield did not significantly increase with N application, the EONR was set at zero. If the yield curve function fitted a simple linear model, the EONR was the maximum N rate used (in this case 202 kg N ha^{-1}). If the yield curve function fitted a quadratic model, the EONR was calculated by setting the derivative of the gross return function in Eq. [1] equal to zero. The gross return was calculated using Eq. [1],

$$\text{Gross return} = (b_0 + b_1 \times \text{N rate} + b_2 \times \text{N rate}^2) \times p_c - p_n \times \text{N rate} \qquad [1]$$

where b_0, b_1, and b_2 are intercept, linear, and quadratic parameters, respectively; p_c is the price of corn; and p_n is the cost of N. The price of corn per megagram was $78.60, and the price of N fertilizer per kilogram was $0.44 at the time of the experiment.

Gross return comparison was made between EONR and a uniform N rate recommendation that would be made by the University of Minnesota (Rehm et al., 1993). For the uniform N application, the recommended rate of 145 kg N ha^{-1} was utilized. Gross return (Eq. [1]) and yield at EONR (YEONR) for both uniform application and the site-specific EONR were calculated using the derived coefficients of response-curve functions for each subblock.

RESULTS AND DISCUSSION

Whole-Field Treatment Effects on Corn Yield

Corn yields from the areas receiving no fertilizer were 6.3, 8.7, and 10.1 Mg ha^{-1} in 1995, 1997, and 1999, respec-

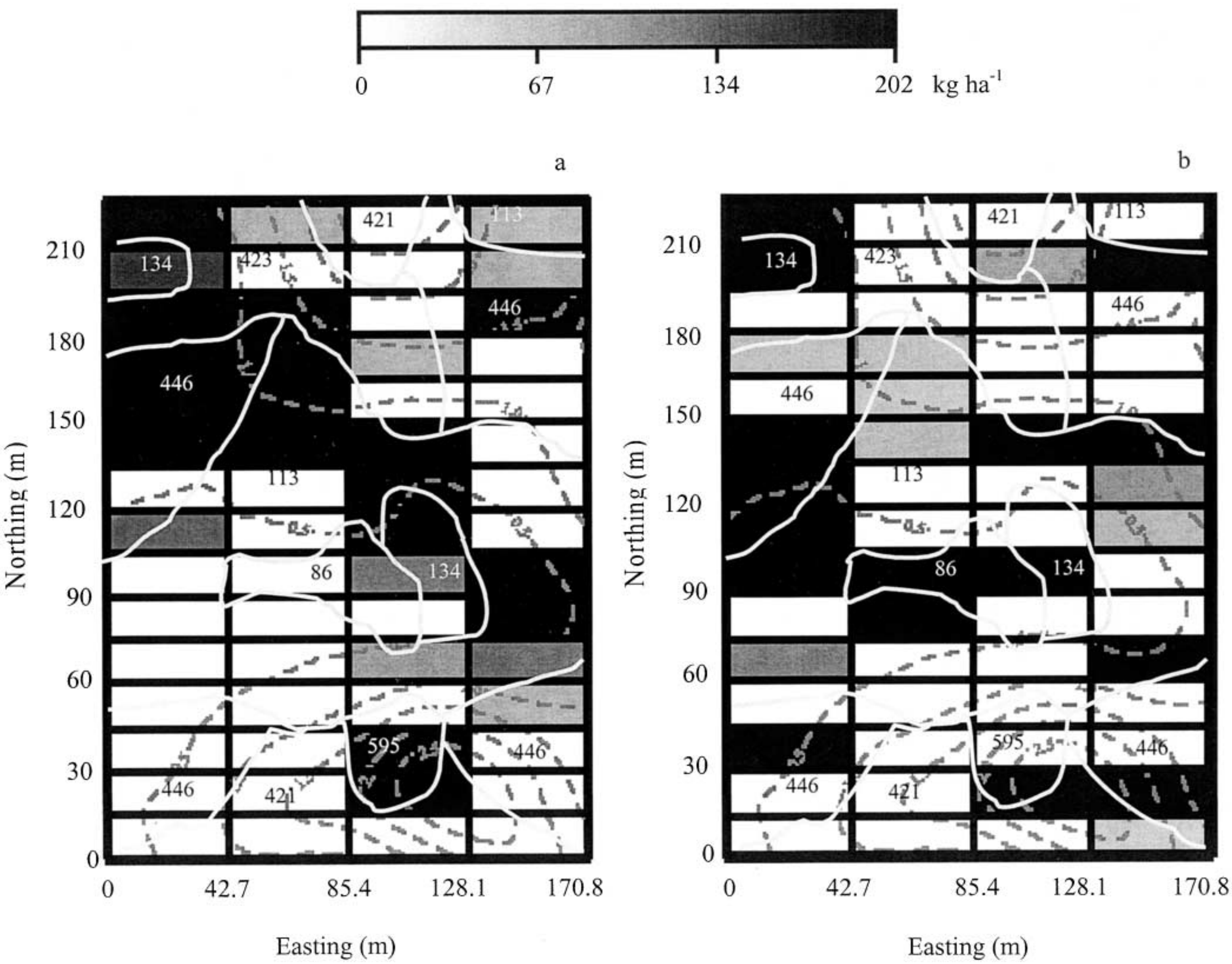

Fig. 3. Spatial distribution of economically optimum N rate (EONR) determined by variable response curve models for corn yield in 1997 (a) and 1999 (b) overlaid with the soil and elevation of the field. (Soil: 86, Canisteo clay loam; 113, Webster clay loam; 134, Okoboji silty clay loam; 421, Ves loam; 423, Seaforth loam; 446 Normania loam; 595, Swanlake loam).

tively (Table 2). Increasing average yield of check plots since 1995 may have been due to hybrid change (Bt corn in 1997 and 1999) and other soil or climatic factors. Nitrogen fertilization significantly increased yields during every year of experimentation. On a whole-field basis, addition of nitrapyrin increased grain yield in 1995 at 134 kg N ha^{-1} but had no effect in 1997 and 1999 (Table 2). These results indicate that the effect of nitrapyrin application on yield is not temporally consistent and would support the findings of Cerrato and Blackmer (1990).

Table 2. The effects of N rate and nitrapyrin on corn yield using nearest-neighbor analysis.

Treatment	1995	1997	1999
	Yield		
kg ha^{-1}	Mg ha^{-1}		
0	6.3d†	8.7e	10.1d
67	7.8c	10.5d	10.8bc
67 + nitrapyrin	7.7c	10.6cd	10.7c
134	8.1b	10.7bc	10.9b
134 + nitrapyrin	8.5a	10.9b	11.1b
202	–	11.2a	11.6a
202 + nitrapyrin	–	11.1a	11.6a

† Values within each column followed by same letters are not significantly different at 0.100 probability level.

Spatial and Temporal Distribution of Yield Response

Corn Yield Response, Economically Optimum Nitrogen Rate, and Yield at Economically Optimum Nitrogen Rate without Nitrapyrin

A large number of the subblocks were not responsive to N treatments (Table 3). In 1997, 33 out of the 60 subblocks and, in 1999, 35 out of 60 subblocks did not significantly respond to the application of N fertilizer.

Table 3. Number of subblocks categorized based on type of yield response curves to N rate.

Year	No response	Simple linear	Quadratic	Total
	Response curve types			
1997	33	17	10	60
1999	35 (60%)†	16 (25%)	9 (0%)	60

† Number in parentheses shows percentage of the same subblocks that remained nonresponsive, linear, or quadratic from 1997 to 1999.

Averaged across both years, approximately 63% of the responsive subblocks followed a simple linear response, and 37% followed a quadratic response. While whole-field analysis suggested yield increases due to N application every year of the experiment, subblock analysis showed yield responses due to N application on less than one-half of the field (Table 3). This suggests spatial variability in organic N mineralization. The nonresponsive areas in 1997 were mostly located in the lower portions of the field where the Webster clay loam is the predominant soil type. The Webster soils generally have higher soil OM contents (40 g kg^{-1}), so the lack of N response may be due to differences in organic N mineralization. These lower landscape positions usually accumulate water, especially in wet years, and would typically be areas of increased leaching, denitrification, or both. The lack of nitrapyrin responses in these areas would also suggest that leaching and denitrification losses were low in both 1997 and 1999, hence supporting the increased N availability via mineralization. Areas of the field requiring the highest rates of N were in the upland positions (mostly the Normania and Ves loams) where soil OM contents ranged from 27 to 33 g kg^{-1}. Favorable growing conditions along with adequate moisture created a high-yielding environment with limited N availability from mineralization because of the lower OM content.

The site-specific EONR derived from the response curves suggests that a majority of the field needed a fertilizer rate lower than the uniform application of 145 kg ha^{-1}, which would have been recommended in 1997 and 1999 (Fig. 3). Likewise, 60% of the nonresponsive subblocks (i.e., EONR = 0 kg ha^{-1}) in 1999 were the same subblocks that were nonresponsive in 1997 (Table 3). Similarly, 25% of subblocks that had an EONR of 202 kg ha^{-1} in 1999 were the same subblocks that required 202 kg N ha^{-1} in 1997. However, subblocks that followed a quadratic response in 1997 did not in 1999. This suggests that there is some temporal effect on the spatial distribution of N response. This also implies that N mineralization from OM is both spatially and temporally variable. The variation in OM mineralization can be

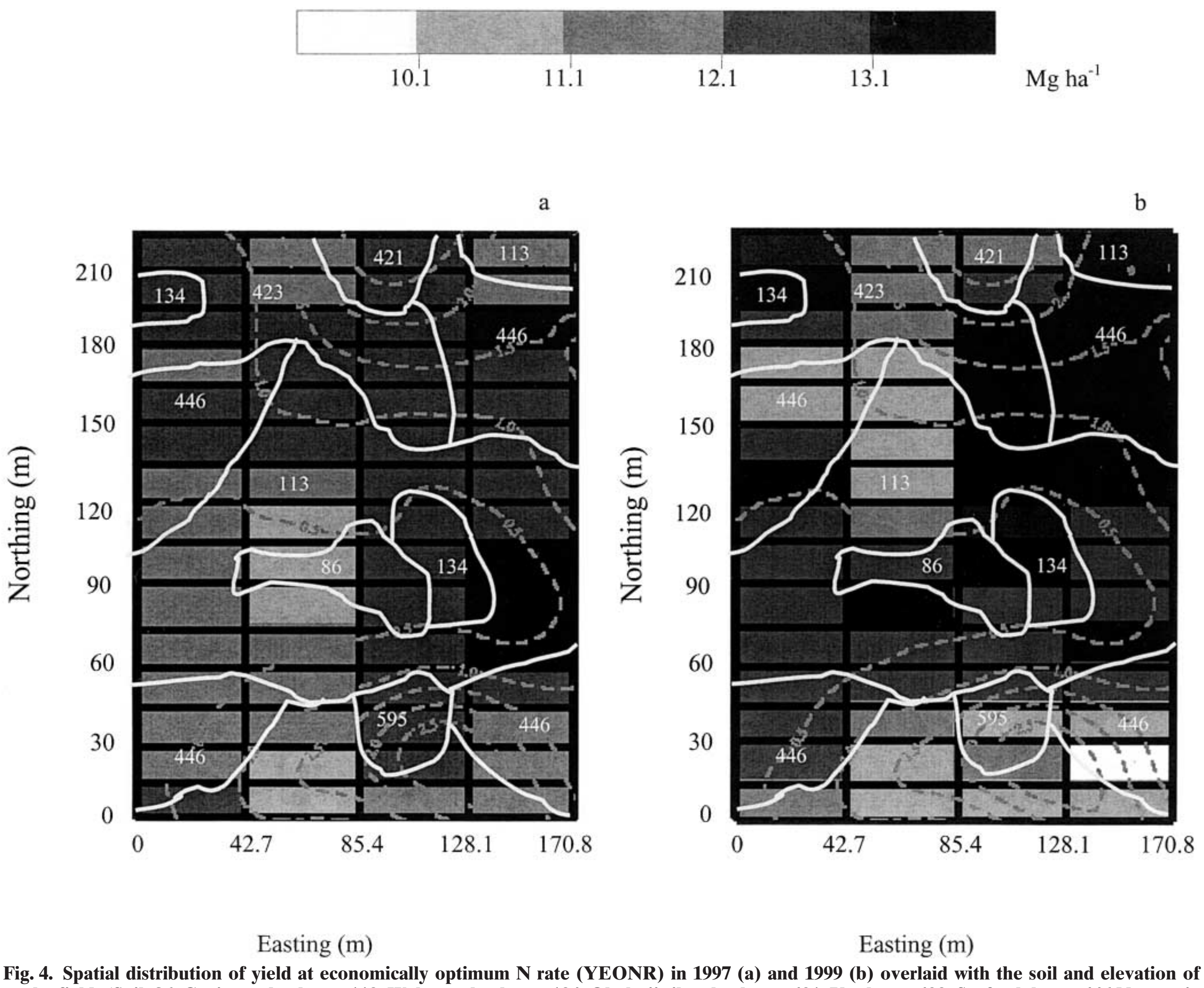

Fig. 4. Spatial distribution of yield at economically optimum N rate (YEONR) in 1997 (a) and 1999 (b) overlaid with the soil and elevation of the field. (Soil: 86, Canisteo clay loam; 113, Webster clay loam; 134, Okoboji silty clay loam; 421, Ves loam; 423, Seaforth loam; 446 Normania loam; 595, Swanlake loam).

influenced by the topography because topography regulates the local hydrological processes (Timlin et al., 1998; Wright et al., 1990). Variable N rate mapped for a given cropping year may vary from year to year depending on the growing season. Nutrient recommendations for variable-rate N application may therefore vary, given the probability of a given season, the knowledge of existing environmental conditions, or both.

Yield at economically optimum N rate varied across the landscape in both 1997 and 1999 (Fig. 4). A large number (28%) of the subblocks that were nonresponsive to N (EONR = 0 kg ha^{-1}) had relatively lower YEONR in 1997 (Fig. 4a), suggesting that factors other than N supply were limiting yield. The YEONR in 1997 was not consistent with YEONR patterns in 1999, indicating temporal effects on the expression of spatial yield variation to N. This temporal inconsistency can be attributed to soil processes (OM mineralization and water availability) that are influenced by topography. Timlin et al. (1998) have observed grain yield variability in landscape due to differences in topography, soil depth, and OM. The portion of the field with the lowest yield (<10 Mg ha^{-1}) was mostly associated with Normania and Ves loam soils located in the highest position of the field. Moulin et al. (1993) have shown higher wheat (*Triticum aestivum* L.) yields in lower elevations where soil has accumulated and lower yields in the eroded areas of higher landscape positions.

Effects of Nitrapyrin on Economically Optimum Nitrogen Rate and Yield at Economically Optimum Nitrogen Rate of Corn

Application of nitrapyrin is intended to slow nitrification of N fertilizer and reduce N loss to maximize available N for crops. Across the entire field, nitrapyrin had no significant influence on yield response. However, when using the unfixed response-curve models for site-specific N application, nitrapyrin either increased, decreased, or had no effects on EONR and YEONR (Table 4). In terms of gross return, the effect of nitrapyrin application was positive in one-half of the field and negative in the other half of the field in both 1997 and 1999.

Table 4. Effect of nitrapyrin application on the spatial distribution of economically optimum N rate (EONR), yield at economically optimum N rate (YEONR), and gross return.

	Number of subblocks		
	Decreased	Increased	No effect
		1997	
EONR	14	17	29
YEONR	24	36	0
Gross return	30	30	0
		1999	
EONR	15	19	26
YEONR	26	34	0
Gross return	29	31	0

The Potential Profitability of Variable Nitrogen Management

The field-average N rate, yield, and gross return of variable N rate and uniform N rate with or without addition of nitrapyrin are presented in Table 5. Due to the lack of consistent nitrapyrin effects on corn yield or gross return, the average value of N across nitrapyrin treatments was used in comparing the variable N rate and uniform N rate application. Averaged across nitrapyrin treatments, the site-specific N rate application would have been 69 or 75 kg N ha^{-1} lower than the current field-average N application in 1997 or 1999, respectively. The field-average yield, however, was similar for the variable N rate and the uniform N rate applications in 1997 and 1999. Consequently, the field-average gross return of variable N management was \$8 or \$23 ha^{-1} higher compared with the uniform N rate application in 1997 and 1999, respectively. Although not measured in this experiment, the environmental benefits associated with the reduced rates of N application while maintaining the same yield also have economic and social benefits.

Spatial distribution of profitability associated with a site-specific EONR was consistently more positive than uniform N management across a majority of the landscape (Table 6). In 1997 or 1999, 93 or 77% of the subblocks were profitable (positive return compared with uniform N management) with variable EONR, respectively. This would be anticipated because uniform applications do not account for the spatial and temporal variability that exists in the field.

Table 5. Field average of N rate, yield at economically optimum N rate (YEONR), and gross return based on variable N rate management vs. a uniform N rate application.

	Variable N rate based on EONR† of unfixed model‡				Uniform N application		
Field average	−nitrapyrin	+nitrapyrin	Avg.		−nitrapyrin	+nitrapyrin	Avg.
				1997			
N Rate, kg ha^{-1}	72.8	80.0	76.4		145	145	145
YEONR, Mg ha^{-1}‡	10.8	10.8	10.8		11.1	11.1	11.1
Gross return, \$ ha^{-1}	818.5	816.0	817.3		806.6	812.1	809.4
				1999			
N Rate, kg ha^{-1}	64.2	75.7	69.9		145	145	145
YEONR, Mg ha^{-1}	11.0	11.1	11.0		11.1	11.2	11.1
Gross return, \$ ha^{-1}	835.6	839.4	837.5		810.6	819.0	814.8

† EONR, economically optimum N rate.
‡ Unfixed model: nonresponsive, linear, or quadratic model depending on the subblock.

Table 6. Spatial distribution of profitability using variable N management compared with uniform N rate application (145 kg ha^{-1}).

	Number of subblocks	
	Profit > 0	Profit < 0
1997	56	4
1999	46	14

CONCLUSIONS

Corn yield increased with N treatments on a whole-field basis; however, spatial analysis showed that corn yield response to N was observed on only half of the landscape. Yield response curves in subblocks depicted various forms, namely: no response, simple linear, or quadratic. Variable EONR was shown to result in potential increased profitability compared with the uniform N application across the field. The EONR was 46 and 52% lower than the recommended uniform N rate and gave \$8 and \$23 ha^{-1} higher profit than the uniform N rate in 1997 and 1999, respectively. The use of nitrapyrin for corn had a positive effect in 1995 but no overall advantage in 1997 and 1999 when N losses appeared to be minimal. Site-specific N management increased profitability and decreased the required N rates when both spatial and temporal variability are considered appropriately. Soil type and elevation across landscape were useful indicators in predicting the magnitude of site-specific N management benefits over uniform N application.

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